The Effect of Forming Diameter and Rotational Speed on Characterization of Formed Tubes by Spinning Process

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Abstract

The spinning process is a common forming process used in the production of various products. It involves shaping sheets and tubes to create industrial products and sizing the connections in tubes. The purpose of this research is to investigate the effects of the final forming diameter and rotational speed on the twist angle, microstructure, hardness, strength, and the weldability in the spinning process of tubes. In this regard, the spinning process was investigated by analytical relations, and experimental tests were performed on copper tubes using a steel mandrel. The results were evaluated using ANOVA analysis. The experiments were conducted using three different diameters and rotational speeds, and the response surface method was used to design the experiments. The analysis of the results revealed that the final forming diameter, or plastic strain, has a significantly greater effect on the mechanical properties and microstructure of the material compared to the rotational speed. An increase in rotational speed and forming diameter leads to a greater twist angle in the tubes. Higher rotational speeds and plastic strain result in increased contact and frictional forces, which cause the temperature to rise within the specimens. Increasing temperature results in grain growth, reduced work hardening, and consequently, a decrease in the material's strength and hardness. At a constant speed, a 25% increase in diameter results in a 47% decrease in hardness and strength. Additionally, using a rotational speed of 1000 rpm and a final diameter of 18 mm can increase the grain size up to three times the initial value and produce a maximum twist angle of 48º in the sample.

1. Introduction

Spinning, or rotary forming, is a metal forming process in which a disk- or cylinder-shaped workpiece rotates around its axis and is gradually formed into the final shape using a forming tool and die. This process has gained significant industrial attention due to its capability to produce complex and diverse geometries, low costs, minimal equipment requirements, and ease of implementation [2 ,1].

In the present study, the effects of final forming diameter and rotational speed on the tube twist angle, microstructure, hardness, strength, and weldability in the spinning forming of tubes are investigated. In this regard, both experimental testing and analytical calculations have been employed

2. Materials and Method

In this study, commercially pure copper tubes with an inner diameter of 14 mm, a wall thickness of 1 mm, and a length of 70 mm were utilized. The mandrel used was made of St37 steel. The copper tube was mounted and formed onto the steel mandrel using a lathe machine. In this setup, the steel mandrel was clamped in the chuck and rotated at a specified speed, while the copper tube was supported by a chuck of tailstock and gradually positioned onto the mandrel. The arrangement of the equipment on the lathe machine is illustrated in Figure 1.

Figure 1 - Setup of the mandrel and copper tube on the lathe machine

To investigate the effects of rotational speed and plastic strain on microstructure, hardness, ultimate strength, tube twist angle, and the weldability potential for the production of bimetallic sections, three

rotational speeds (355 rpm, 500 rpm, and 1000 rpm) and three mandrel diameters (14.5 mm, 16 mm, and 18 mm) were employed. Based on these parameters, the experiments were designed using the response surface method, and the results were analyzed through ANOVA analysis.

After forming process, the specimens were first evaluated for weldability using simple tensile tests. To assess the amount of tube twisting during the forming process, the twist angle was measured on the sample surfaces by imaging the marks of material flow. For microstructural analysis, after metallographic preparation, the microstructure was examined using an optical microscope. The average grain size was determined by the intercept method according to ASTM E112-96 [3], averaging measurements in both the vertical and horizontal directions. For hardness measurements, three points positioned 120 degrees apart on each sample cross-section were tested using the Vickers hardness method, and the average of these values was reported as the mean hardness. To estimate the tensile strength of samples, hardness test results were utilized. The tensile strength was estimated using Equation (1), where Sut represents the tensile strength in MPa and HV denotes the Vickers hardness value [4].

$$S_{ut} = 3.353 \times HV \tag{1}$$

3. Governing Equations

According to the experimental observations, the length of the specimens showed no significant change before and after the forming process, indicating that the axial strain is negligible. Assuming material homogeneity and volume constancy, Equation (2) can be expressed. Consequently, the true strain in the thickness direction can be determined using Equation (2), where D is the diameter, t is the wall thickness, and ε_t represents the true strain in the thickness direction.

$$t_1 D_1 \pi = t_2 D_2 \pi \quad \rightarrow \quad \frac{t_2}{t_1} = \frac{D_1}{D_2}$$
$$\varepsilon_t = \ln\left(\frac{t_2}{t_1}\right) = \ln\left(\frac{D_1}{D_2}\right) \tag{2}$$

Considering that the sum of strains must always equal zero [6, 5], the hoop strain (ε_c) is the negative of the thickness strain, as shown in Equation (3)

$$\varepsilon_c = -\varepsilon_t = -\ln\left(\frac{D_1}{D_2}\right) = \ln\left(\frac{D_2}{D_1}\right) \tag{3}$$

4. Results and Discussion

Based on Equations (2) and (3), whatever the difference between the initial and final diameters be greater, the true strains in both the thickness and hoop directions are greater. Accordingly, the specimen formed to a final diameter of 18 mm experienced the highest strain, with a value of 0.251, while the specimen with a final diameter of 14.5 mm exhibited the lowest strain, with a value of 0.035. Table 1 presents the measured values of hardness, ultimate strength, twist angle, true thickness strain, and grain size for the samples.

Analysis of the results using ANOVA revealed that both the final diameter (or plastic strain) and the rotational speed were significant influencing factors, with p-values less than 0.05 in all cases. However, the effect of plastic strain is significantly greater than that of rotational speed.

4.1. Twist Angle

Inserting the copper tubes onto the steel mandrel under rotational conditions and frictional contact causes the copper tubes to twist to a certain degree. Due to the rotational movement of the mandrel inside the copper tube and the presence of friction, both heat and torsional torque are generated. With increasing the plastic strain, due to more plastic deformation, the contact force between the copper tube and the mandrel increases. As strain and rotational speed increase, the torsional torque and heat generated also intensify. This leads to a greater twist angle in the specimens. Figure 2 illustrates the effects of plastic strain and rotational speed on the twist angle.

Table 1. Strain in the thickness direction, twist angle, hardness, ultimate strength, and grain size of the formed samples

| Sample No.	Rotational speed (rpm)	Mandrel Diameter (cm)	Strain ε_t	Twist Angle (^{0})	Hardness (HV)	Tensile Strength (MPa)	Grain Size (μm)
1	355	14.5	0.035	0	125.36	420.33	2.76
2	355	16	0.133	12	75.56	253.35	4.59
3	355	18	0.251	26	67.7	226.99	4.25
4	500	14.5	0.035	0	117.36	393.5	2.53
5	500	16	0.133	18	67.56	226.52	4.63
6	500	18	0.251	33	63.26	212.11	5.78
7	1000	14.5	0.035	0	117.36	393.5	3.02
8	1000	16	0.133	15	67.53	226.42	5.63
9	1000	18	0.251	48	58.8	197.15	10.03
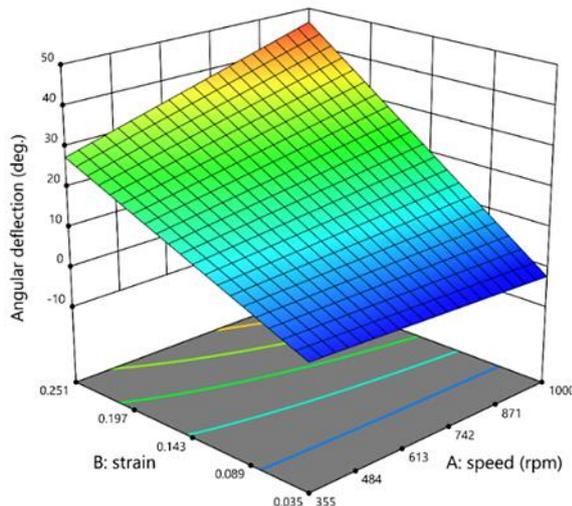
Figure 2. Interaction of plastic strain (forming diameter) and rotational speed on the twist angle

4.2. Grain Size

Examination of the samples prior to forming revealed that the copper tubes exhibited a fine-grained, strain-hardened structure due to their production by extrusion process. Based on grain size measurements, it was observed that increasing the rotational speed and forming diameter led to grain growth. This results from the interaction of process parameters and the associated rise in frictional heat. An increase in rotational speed enhances the temperature due to friction, and a higher plastic strain, due to greater plastic deformation, causes an increase in contact and frictional forces, leading to more heat generation. The elevated temperature during the forming process activates recovery and grain growth mechanisms [7]. Figure 3 illustrates the interaction of plastic strain and rotational speed on the grain size, and Figure 4 presents the microstructures of selected samples.
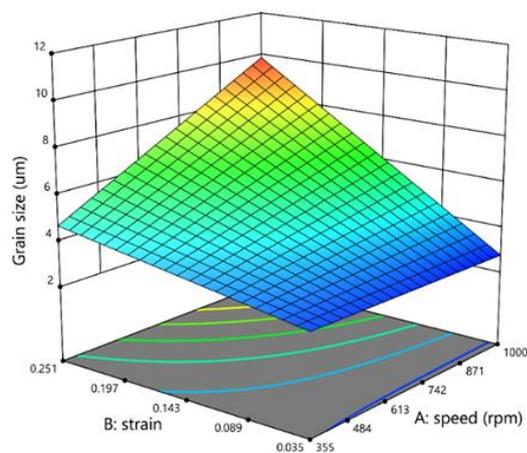

Figure 3. Interaction of plastic strain (forming diameter) and rotational speed on grain size
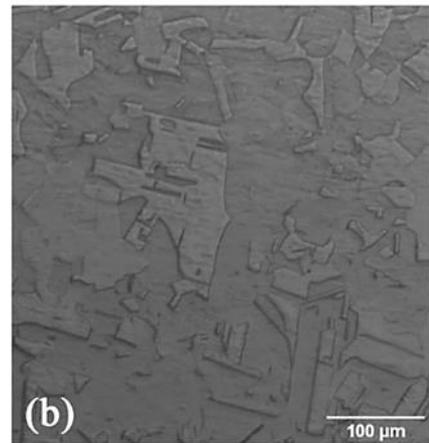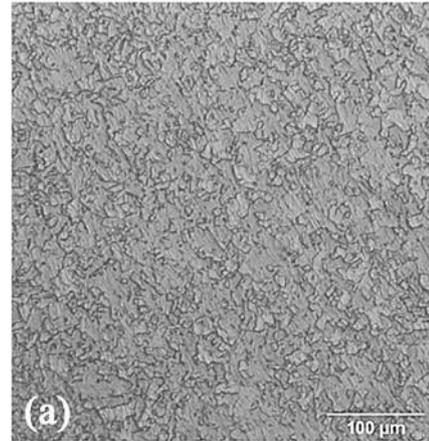

Figure 4. Microstructures of formed samples: (a) diameter 14.5 mm, rotational speed 355 rpm; (b) diameter 18 mm, rotational speed 1000 rpm

4.3. Hardness and Strength

In copper alloys, hardness and tensile strength are directly related, with the ultimate strength being a multiple of hardness. Evaluation of the results showed that, consistent with the observations regarding microstructure and grain size, the hardness and strength of the samples decreased with increasing rotational speed and forming diameter. This behavior is attributed to the temperature rise during the forming process, grain growth, and reduction in work hardening, as previously discussed. The measured hardness and strength values indicate that at a constant rotational speed, a 25% increase in forming diameter results in a 47% decrease in hardness and strength.

Figure 5 shows the effect of the interaction between plastic strain and rotational speed on the hardness of the samples.
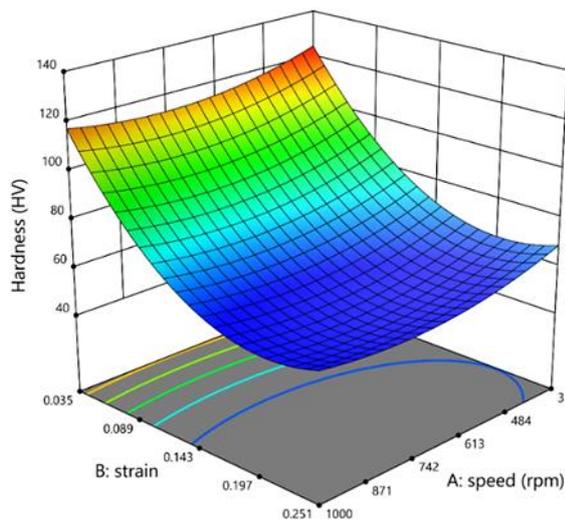
Figure 5. Interaction of plastic strain (forming diameter) and rotational speed on hardness.

4.4. Weldability

Evaluation of the weldability between the copper tubes and the steel mandrel revealed that none of the tubes were welded to the mandrel and were easily separated. This indicates that the elastic–plastic forces, temperature, and frictional conditions were insufficient to achieve bonding between the two materials. The production of bimetallic tubes similar to those manufactured by flow forming [8, 9] requires significantly higher forces and cannot be achieved through this method

5. Conclusions

Rotary forming is one of the common metal forming methods, extensively used for shaping sheets and tubes. In this study, the effects of rotational speed and final diameter (strain) on the mechanical properties, and microstructure were investigated through analytical relations, experimental tests and ANOVA analysis. The results are summarized as follows:

- The investigation of results showed, plastic strain (forming diameter) and rotational speed are influenced parameters while, plastic strain having a significantly stronger effect compared to rotational speed.
- The evaluation of the twist angle indicated that increasing the plastic strain and rotational speed led to a greater twist angle. Regardless of the rotational speed, at low levels of plastic strain, the twist angle was negligible.
- The study of microstructures showed that an increase in rotational speeds and forming diameters resulted in grain growth due to the increase in frictional heating induced by the interaction of process parameters.

Analysis of the hardness and strength results revealed that both decreased with increasing rotational speed and forming diameter. This is due to reduced work hardening caused by frictional heating, activation of recovery mechanisms, and grain growth.

- The examination of the weldability of the copper tube to the steel mandrel demonstrated that the elastic–plastic forces, temperature, and frictional conditions were insufficient for bonding. Hence, producing bimetallic tubes requires significantly higher contact forces, which cannot be achieved through this process

6. Acknowledgment

7. References

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